



Feasibility of NASA TT&C via Commercial Satellite Services

W. Carl Mitchell
Space Systems/Loral, Palo Alto, California

Roland Weiss
Lockheed Martin Space Missions Systems and Services, Seabrook, Maryland

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ACRONYM LIST

Al	Aluminum	LM	Lockheed Martin Space Mission Systems and Services
ASIC	Application Specific Integrated Circuit	SMS&S	
		LO	Local Oscillator
AuC	Authorization Center	MHz	MegaHertz
CDMA	Code Division Multiple Access	MOCC	Mission Operations Control Center
CMD	Command	MSS	Mobile Satellite Service
CMOS	Complementary Metal-Oxide Semiconductor	NAM	Number Assignment Module
CSCN	Commercial Satellite Communications Network	NASA	National Aeronautics and Space Administration
CSCS	Commercial Satellite Communications Service	PI	Principal Investigator
EIRP	Effective Isotropically Radiated Power	PLMN	Public Land Mobile Network
ESN	Electronic Serial Number	PN	Pseudo-Noise
EM	Engineering Model	POC	Point of Contact
FCC	Federal Communications Commission	ROM	Rough Order of Magnitude
GLP	Globalstar Limited Partnership	PSTN	Public Switched Telephone Network
GOCC	Ground Operations Control Center	Rad	Radiation Absorbed Dose
GPS	Global Positioning System	RX	Receive
GSFC	Goddard Space Flight Center (NASA)	RAS	Radioastronomy
GSM	Group Speciale Mobile	RF	Radio Frequency
GTS	Gateway Transceiver Subsystem	SS/L	Space Systems/Loral
GW	Gateway	SMSS	Space Mobile Satellite Services
HLR	Home Location Register	SOCC	Satellite Operations Control Center
kbps	Kilobits per Second	SP	Service Provider
KHz	KiloHertz	SS 7	Signaling System #7
LEO	Low Earth Orbiting	SSD	Shared Secret Data
LNA	Low Noise Amplifier	TIM	Technology Interchange Meeting
ISDN	Integrated Services Digital Network	TLM	Telemetry
		T&C	Telemetry and Command
		TT&C	Telemetry, Tracking, and Command
		TX	Transmit
		UT	User Terminal
		VLR	Visitor Location Register

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SECTION 1 – INTRODUCTION

This report presents the results of a study to identify impacts and driving requirements imposed by augmenting traditional National Aeronautics and Space Administration (NASA) space-ground communications to/from satellites in low earth orbit (LEO) with a commercial satellite communications service, such as Globalstar or Iridium, etc. Because of its relatively high orbit altitude, Globalstar is the leading candidate for this augmentation, and the study used the Globalstar network to illustrate specific operational needs and concepts and to provide preliminary focus for conclusions. The commercial satellite communications service (CSCS) would be used to relay spacecraft and instrument commands, health and safety (engineering) telemetry, and compressed quick-look science data. NASA's goal is to lower the cost and increase the flexibility of spacecraft operations by using a commercial communications service instead of maintaining and operating its own communications infrastructure. This potential communications service is called "Space Mobile Satellite Service" (SMSS) within this report.

In addition to cost savings, the potential SMSS service must also increase operational flexibility. Increased operational flexibility is perceived to be as important to the science spacecraft user as cost reduction. Current space-to-ground communications networks such as TDRSS are typically resource limited as compared with the demand. Communications assets must be scheduled weeks in advance and are configured according to the schedule to support each spacecraft user. Use of a commercial network offers the opportunity to contact a spacecraft on a nearly "on-demand" basis with ordinary phone calls. If feasible, such increased flexibility offers the potential to increase scientific productivity by allowing scientists to react in near real time to transient or unpredictable science events.

1.1 SMSS CONCEPT OVERVIEW

SMSS service would be used by NASA spacecraft with orbits lower than that of the commercial satellite constellation. As shown in Figure 1-1 with the Globalstar system as an example, the NASA spacecraft would use a new, space qualified SMSS User Terminal (UT) as its low rate communications system. The spacecraft communicates with its Mission Operations Control Center (MOCC) via the commercial satellite communications network (CSCN) -- which for Globalstar consists of 48 LEO satellites and strategically placed Gateways (GWs) -- and the Public Switched Telephone Network (PSTN). Globalstar GWs are located around the globe and are operated by Globalstar Service Providers. These Service Providers (AirTouch in the United States) provide the end-to-end Globalstar service (including billing, Globalstar Gateways, location mobility registers, and terrestrial communications services). A NASA Point of Contact (POC) serves as a central point of contact between users, the CSCN, and Service Providers. Table 1-1 provides a list and high level description of the SMSS elements using Globalstar nomenclature.

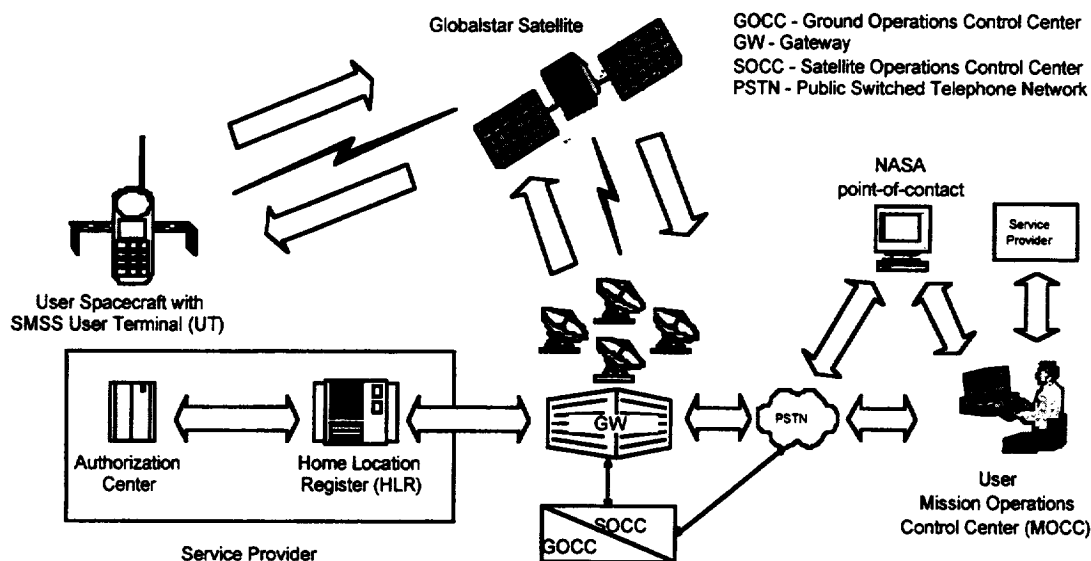


Figure 1-1. High Level SMSS Concept

Table 1-1. Description of SMSS System Elements (Globalstar as nominal example)

SMSS System Element	High-Level Description
Globalstar Satellite	One of 48 satellites in full constellation; 8 planes with 6 satellites in each plane Orbit: 1400 km, 52° inclination, circular, 113.7 minimum orbit
Gateway	Communications gateway between Globalstar and the Public Switched Telephone Network (PSTN) Supports Telemetry and Command (T&C) for the Globalstar satellite constellation Typically includes Visitor Location Register (VLR)
Ground Operations Control Center (GOCC)	Manages Globalstar communications network Functions include network management, resource allocation, contact scheduling
Satellite Operations Control Center (SOCC)	Manages Globalstar satellite constellation (including spares) Responsible for health, safety and orbit maintenance
SMSS User Terminal (UT)	Modified and space-qualified terminal, based on Globalstar terrestrial terminal
Service Provider (e.g., AirTouch in United States)	Provides end-to-end Globalstar service, including billing
Home Location Register (HLR)	In U.S., typically part of Service Provider's existing infrastructure Stores user profile (including current location) Accessed by VLR in remote Gateway through PSTN via separate dedicated signaling network
Authorization Center (AuC)	Part of Service Provider's infrastructure Supplies user authentication data. May be accessed by HLR
NASA Point of Contact (NASA POC)	Distribution point of Globalstar-provided data (ephemerides, schedules, status)
Mission Operations Control Center (MOCC)	Manages and controls user spacecraft (bus and science instruments) All mission operations functions from science planning through flight operations

High-rate science data, if needed, is communicated separately from the CSCN via low cost, receive-only autonomous ground stations. SMSS calls would typically be initiated by the MOCC responsible for spacecraft operations. However, the spacecraft could "call home" in response to observed safing or science events.

1.2 STUDY PURPOSE/SCOPE

The study examined the feasibility of the SMSS service at a high level and developed a top-level description of the required functionality to support a NASA decision to proceed with further studies. NASA suggested that study illustrations use Globalstar based on internal NASA studies which found that Globalstar was a promising candidate and on Globalstar being willing to offer information pertinent to such a study. While NASA provided a set of strawman "requirements," NASA hopes to use the CSCS "as is" if possible. NASA actively encouraged the study team to provide feedback on the requirements impacts, and to propose requirements changes to reduce impacts. The objective of the study was to determine whether there was a sufficient match between these NASA requirements and a CSCS (e.g., Globalstar) capabilities and to perform an initial assessment of the impact on CSCN/SMSS elements to provide the SMSS.

The NASA Spartan mission was the source of requirements for this study. However, other potential missions targeted for this service include the NASA LEO Explorer Missions (UNEX, SMEX, MIDEX), the earth systems science Pathfinder missions, NASA's "low cost access to space" missions (including Spartan, Ultralight and secondary payloads, and research balloons). NASA's ultimate hope is that as CSCSs improve, they would become the primary communication link for all NASA LEO missions.

1.3 SUMMARY

Impacts were identified on most CSCN/SMSS system elements illustrated in Figure 1-1. Also, it was found that a SMSS based on Globalstar with eight optimally placed GWs can meet or exceed the NASA requirement of one contact per orbit for spacecraft in lower orbits which are inclined between 28 and 52 degrees. A spacecraft receiving service would be expected to supply its orbital position to the CSCN system via the SMSS UT. In addition, the satellite SMSS UT should be designed with minimal radio frequency (RF) losses and filtering may be required to meet flux density limits in Radio Astronomy Service (RAS) bands. A newly configured and space qualified UT would be developed, hopefully, from existing components from Globalstar terrestrial terminals.

While no showstoppers were identified, impacts were found on each system element, and SMSS feasibility was not demonstrated. The study team concludes that follow-on efforts are thus both justified and required. Section 4 of this report describes the study team's recommendation that NASA develop the SMSS concept in three incremental phases:

1. Validate and extend from a technical, regulatory, and Globalstar Service Provider standpoint, the operations concept, impacts and derived requirements, link analysis, strawman UT design, and schedule which were developed in this study.
2. Develop system-level requirements and functional designs supporting a final assessment of risks and feasibility and a go/no-go decision.
3. Detailed design, development, and test of the elements and end-to-end test of the SMSS service

1.4 REPORT ROADMAP

Section 2 of this report summarizes the background and objectives of the study, and provides an overview of the SMSS operations concept. Section 3 presents the impacts identified and summarizes imposed (derived) requirements on each system element. Section 3 also presents the results of analyses performed on the RF link budget, the orbital contacts and coverage requirements, and of the ability to produce an affordable SMSS UT. Section 4 presents the study team's recommended approach to follow-on studies.

SECTION 2 – STUDY BACKGROUND AND OBJECTIVES

The study team consisted of Space Systems/Loral (SS/L), and Lockheed-Martin Space Mission Systems and Services (L-M SMS&S), with technical input provided by GLP in consultation with its Code Division Multiple Access (CDMA) partner, Qualcomm, Inc. SS/L focused on the link analysis and the onboard UT. L-M SMS&S organized and chaired the meetings, developed the end-to-end operations concept, performed the requirements analysis and the contact/coverage analysis, examined user MOCC issues, and drafted this final report. Technical advice was provided by GLP on the Globalstar system and its interfaces, security, flight demonstration, and follow-on schedule issues.

This study was initiated to support a decision by NASA on whether to proceed with follow-on feasibility and other studies. The study consisted of three tasks. First, impacts and driving requirements on the Globalstar system of the SMSS service were identified based on the NASA-imposed service requirements. Second, recommended schedules including a flight demonstration were developed. Third, the results were documented in the following three proprietary reports:

1. Feasibility of NASA TT&C Via Commercial Satellite Services (TRCSS), Kickoff Meeting Notes, July 16, 1996
2. Feasibility of NASA TT&C Via Commercial Satellite Services (TRCSS), First Technology Interchange Meeting (TIM), September 5, 1996
3. Feasibility of NASA TT&C Via Commercial Satellite Services (TRCSS), Draft Final Report, December 20, 1996 (same as this Final Report but includes as appendix material the viewgraphs presented at the second TIM, held on November 7, 1996)

This present non-proprietary Final Report is virtually the same as the Draft Final Report but omits the proprietary appendix material.

The study approach combined three working meetings with selected analyses and research to identify impacts and driving requirements imposed by the NASA requirements. Meetings were held between the study team and NASA representatives at GLP facilities in San Jose, California. The kickoff meeting was held in July 1996 to discuss NASA programs, NASA requirements, operations concepts, internal GSFC study results, Globalstar status, and the study plan. The results of this meeting are provided in a separate report (item 1 above). Selected analyses and study efforts were then performed. These efforts often relied on expert opinion; comprehensive and detailed engineering studies were not performed. Results were presented at two technical interchange meetings (TIMs) at GLP on September 5, 1996 and November 7, 1996.

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SECTION 3 – RESULTS

The study developed a workable operations concept for a Globalstar-based SMSS, as an example, identifying impacts on each of the major system elements. More detailed analyses of the link, orbital contacts and coverage, and the flight-qualified UT are presented in the subsections below. While no technical showstoppers were identified, some impacts were identified on most of the SMSS system elements illustrated earlier in Figure 1-1. Similar system-level impacts may be supposed to exist for SMSS systems based on other MSS systems.

3.1 END-TO-END SYSTEM ANALYSIS

Two end-to-end efforts were conducted. First, an end-to-end operations concept was developed which showed how system elements interact over time to provide the SMSS. Second, the impacts and requirements imposed on each system element were identified.

3.1.1 Operations Concept

The SMSS operations concept developed in this study is end-to-end in both time (from pre-contact through post contact) and space (from user spacecraft to ground system MOCC). This concept was developed iteratively in discussions between Lockheed Martin, GLP, and Qualcomm.

The complete operations concept provides two end-to-end scenarios (mentioned above) and four detailed supporting scenarios: scheduling and status, detailed call processing, security, and billing. An overview of call processing in the Globalstar system and a description of the major decisions and issues discovered are presented here.

3.1.1.1 UT-Terminated Call Scenario

Routine spacecraft operations are supported by a UT-terminated call (MOCC places the call to the UT). The scenario is shown in Figure 3-1. Detailed call processing steps are illustrated in Figure 3-2 and described in Table 3-1. Major SMSS system elements are identified on the left side of the figure, and time elapses as you move to the right side of the figure. For each contact:

- a. During the pre-contact period, the NASA POC would receive a daily update of the weekly Globalstar ephemerides and Globalstar tracking schedule. The tracking schedule includes information concerning Gateway and antenna availability. The POC then computes a weekly contact schedule (a list of all possible contacts) for each NASA spacecraft and distributes the contact schedule to the User MOCCs daily.

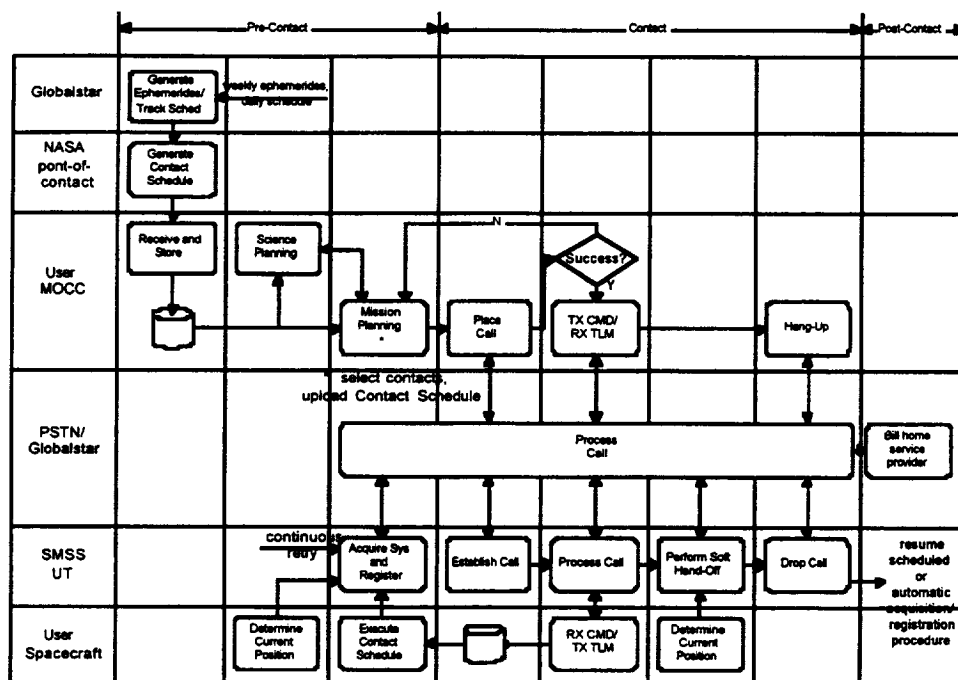


Figure 3-1. End-to-End Scenario For UT-Terminated Call

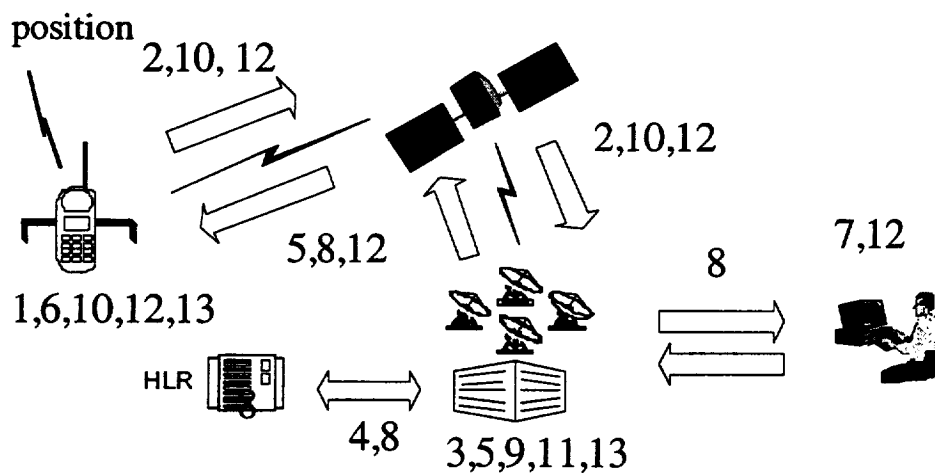


Figure 3-2. Detailed Call Processing of UT-Terminated Call

Table 3-1. Description of UT-Terminated Call Processing Steps

Steps	Description
Acquire System and Register	<ol style="list-style-type: none"> 1. UT is activated based on Contact Schedule, acquires pilot/sync channel for authorized GW; begins monitoring paging channel 2. Registration Request sent to GW – includes UT position 3. GW accepts UT's position and maps to service provider(s) 4. Signaling message sent to user's HLR; HLR provides user profile to GW 5. GW authenticates UT and service provider is selected
Place/Establish Call	<ol style="list-style-type: none"> 6. UT continues to monitor paging channel 7. User MOCC places call based on computed Contact Schedule (via modem pool/ISDN) 8. Service provider determines UT location by polling HLR 9. GW receives call from service provider; sends paging message 10. UT responds and sets up channel 11. GW sets up channel; connects to UT
Process Call	<ol style="list-style-type: none"> 12. Duplex message traffic
Perform Soft Hand-Off	<ol style="list-style-type: none"> 13. Perform Soft Hand-Off, as needed <ol style="list-style-type: none"> a. UT detects new pilot (beam); notifies GW b. UT provides position update to GW c. GW acquires forward channel; notifies UT d. Two channels used until power on the original channel drops below threshold 5. Hang-up
Drop Call	<ol style="list-style-type: none"> 14. Hang-up; call ends as scheduled by user MOCC

Note: Use of a contact schedule:

1. Assures that contacts will be of sufficient duration to be useful
 2. Assures that Doppler limits are not exceeded
 3. Reduces unnecessary registration traffic as the UT changes location in its orbit
 4. Avoids transmitting near RAS sites when these sites are active.
- b. The User MOCC receives the contact schedule, provides it to the scheduling system, and selects the contacts that it will use. The contact schedule is uploaded to the UT/user spacecraft during an SMSS contact to support scheduled enabling of the UT.
 - c. When the UT is enabled, it listens for an SMSS equipped Gateway and registers its position with the Visitor Location Register (VLR) of the Gateway being visited. The spacecraft provides the UT with the needed position data, which is transmitted to the visited Gateway. The visited Gateway updates the user's Home Location Register

(HLR) with the location of Gateway being visited by the UT and receives the user's profile, all via a separate Signaling System #7 based dedicated signaling network.

- d. To receive telemetry or to command the spacecraft, the MOCC places phone calls during any of the scheduled contact periods. Calls are made through the PSTN, with call setup occurring via the PSTN's separate channel signaling network. The call is directed to the visited Gateway, which is known to the user's HLR. The MOCC receives engineering telemetry and quick-look data, and uploads commands all via the PSTN. If the call fails, the MOCC may try again either during the same contact period or during the next period.
- e. Billing data is processed during the post contact period. A single bill is sent to the user via the normal Globalstar Service Provider process. Although SMSS data calls will be billed at a rate proportional to the actual data throughput (up to approximately four times the rate of voice calls), the actual rates have not yet been determined. When the call is terminated, standard protocols are used to determine air time at the Gateway for billing purposes. Accounting for the PSTN portions of the call will be established by the long distance carriers. A single consolidated bill statement is sent by the Globalstar Service Provider to the NASA POC, who forwards it to the SMSS User. The NASA POC could conceivably add a surcharge on each bill for any additional NASA-unique services which the POC provides.

3.1.1.2 UT-Initiated Call Scenario

A UT-initiated call is used during special circumstances such as safing emergencies or science events. The pre- and post-contact steps are generally the same as for a UT-terminated call, and are illustrated in Figure 3-3. The detailed call processing steps are illustrated in Figure 3-4 and described in Table 3-2. The UT is activated, listens for the identification of an SMSS equipped Gateway, and registers its position. The visited gateway informs the HLR that the UT is visiting and receives the user profile as described previously. For each contact:

- a. The UT attempts to access the Globalstar system based upon the contact schedule. If the contact schedule is not available or is invalid, the UT continuously attempts to access the Globalstar system until contact with the MOCC is established. Continuous mode might be used, for example, before a contact schedule is loaded, or as a backup mechanism if the spacecraft has not had contact with the MOCC within a specified period.
- b. When contact is established, the calls are made through Globalstar and the PSTN to the user MOCC, with call setup occurring via the PSTN's separate channel signaling network. The call is directed to the user's home Gateway, which is known to the VLR of the Gateway being visited, and from there to the MOCC via the PSTN. The user spacecraft then generates messages of satellite safing status and/or science events. A

response from the MOCC on the forward channel will occur if the transmission is successful. Optionally, the UT could use PSTN voice mail service to log the call and to alert the MOCC. Logging of the UT phone call by itself provides notification of an emergency. The MOCC stores messages and pages the flight operations team as required (assuming the MOCC is unstaffed). The UT would remain in continuous mode until contact with the MOCC is fully established.

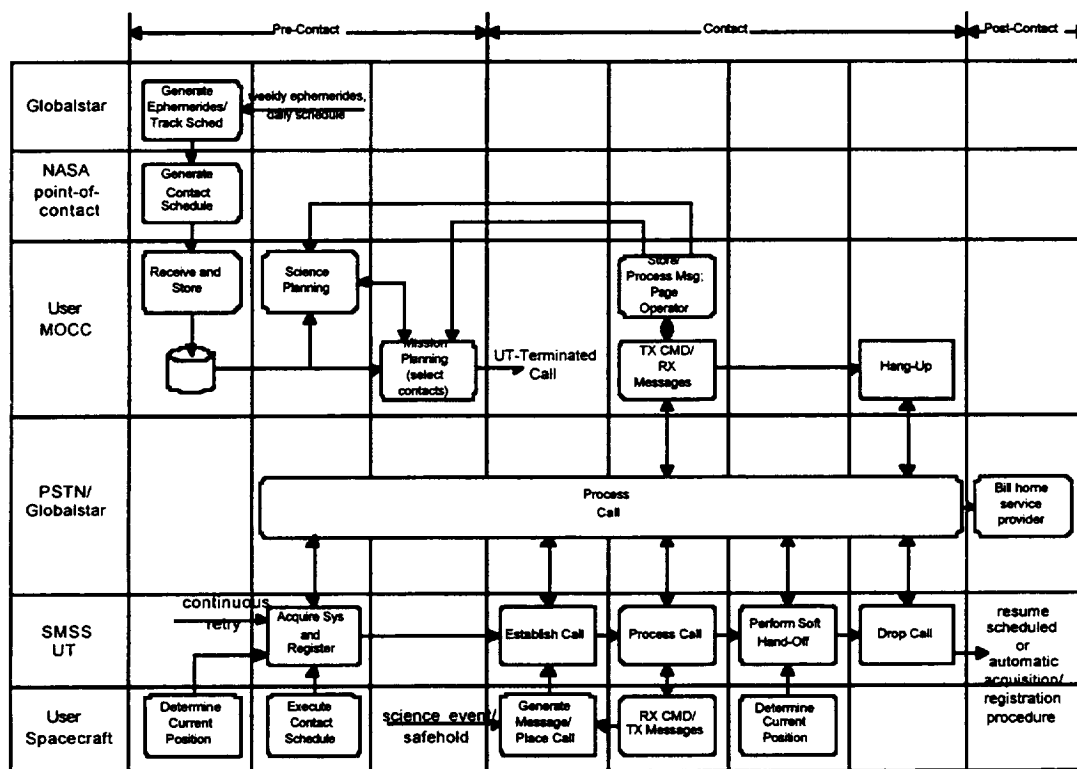


Figure 3-3. End-to-End Scenario For UT-Initiated Call

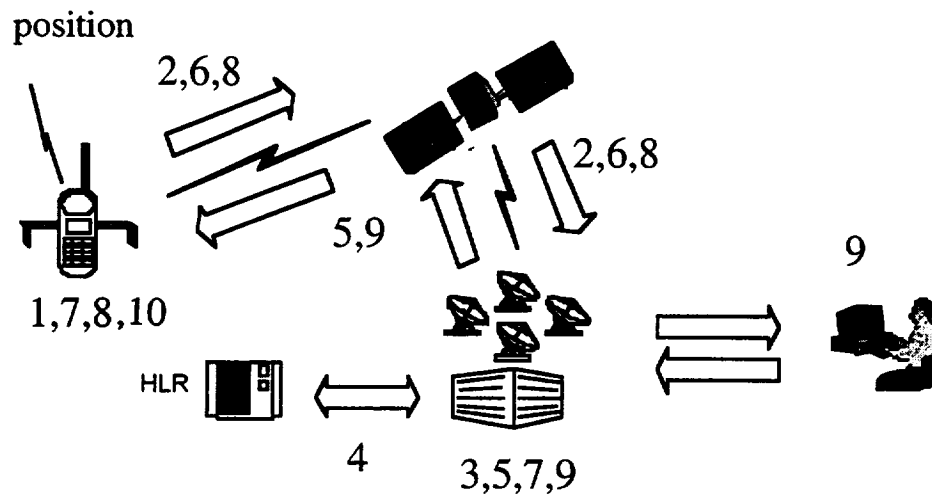


Figure 3-4. Detailed Call Processing For UT-Initiated Call

Table 3-2. Detailed Call Processing of UT -Initiated Call

Steps	Description
Acquire System and Register	1. through 5. — same as UT-Terminated call 1. through 5. in Table 3-1
Establish Call	6. Origination Request sent to GW 7. GW and UT set up traffic channel
Process Call	8. UT begins processing call, sends short messages 9. MOCC responds as appropriate
Drop Call	10. Call ends based on Contact Schedule uploaded from MOCC

As described in Table 3-3, this operations concept meets NASA's desire for improved flexibility over existing space-ground communications. While schedules are computed to ensure contacts of sufficient duration and to comply with Doppler and other constraints, these schedules are not used to configure the ground system. Phone calls (contacts) can be made at any of the acceptable periods. If a valid schedule is unavailable, the UT will operate in continuous mode until contact is made.

Table 3-3. Comparison of Scheduling Using Non-SMSS vs SMSS

Function/Event	Non-SMSS Mission	SMSS Mission
Scheduling concept	Current - Scheduling requests submitted to network infrastructure with long lead time required; schedule may not be optimal to achieve science objectives; Operations intensive execution Future - Increasing autonomy/automation of ground stations	Driven by predictable contact schedule; simple, inexpensive, autonomous process; computed centrally by the NASA POC
Competition for resources	Share TT&C resources with other missions (resources limited as compared with demand)	Share resources with other Globalstar users (resource rich, availability > 99.9%)
Rescheduling impacts (close to or during contact)	Missed pass and lengthy re-scheduling process.	Re-try call on same pass or next pass
Support for near real time science events	No	Yes, less than one orbit on average (~90 min.)
Identification of science events	Slow, requires processing quick-look	Fast (with on-board autonomous detection)
Scheduling scenario	Long-term scheduling of fixed science observations	Long-term scheduling of science observations plus able to react to real-time events
	Medium-term scheduling of spacecraft constraints and space/ground system communications assets	Medium-term scheduling of spacecraft constraints only (generate list of all possible SMSS contacts)
	Short-term scheduling to configure ground system communications assets	On demand access to communications assets (normally select from contact list; if list invalid, continuously retry)
	Contingency rescheduling (target of opportunity)	
	Emergency scheduling (safing)	

3.1.2 Impacts and Driving Requirements

NASA provided the study team with a set of high-level requirements at the kickoff meeting. Impacts of these requirements were identified via either development of the operations concept or the more detailed UT analysis, link analysis, and contact analysis. A set of "representative" imposed or derived requirements were developed. These requirements are representative in that they are examples, and are neither sufficiently detailed nor comprehensive enough to support proceeding without additional work. In some cases, the study team recommends that NASA modify its requirements.

The major impacts are summarized here:

- a. Spartan Spacecraft: First, the spacecraft will be expected to provide its position to the UT. Second, the spacecraft must activate the UT according to a stored schedule of all possible contacts, or operate in continuous mode. Third, the spacecraft must also provide for antenna switching based on spacecraft attitude.
- b. Contact/Coverage: Implementation of SMSS service at eight strategically placed gateways is sufficient for the system to meet or exceed the NASA requirements of one five-minute contact per orbit for spacecraft between approximately 28 and 52 degrees inclination. One contact per two orbits is supported for polar orbiting spacecraft at or below an altitude of 600 kilometers. Since most NASA polar spacecraft are at altitudes significantly greater than 600 kilometers, there may be few polar users. Further study is required to confirm this conclusion, and also to better characterize coverage between 52 and 90 degrees inclination. Eliminating satellite soft handoffs (i.e., limiting contacts to a single satellite) has little effect on contact frequency or duration for users with altitude greater than 400 kilometers. Requiring all contacts to be within a Doppler limit had little or no effect on contact frequency or duration at all altitudes considered. The greatest effect of the Doppler limitation was at 90+ degree inclination cases and altitudes less than 900 kilometers. The eight Gateway locations chosen for this study were the four Gateways where Globalstar telemetry and commanding hardware is to be installed, plus four locations chosen to provide global SMSS coverage. Further study is required to determine the effect of choosing other Gateway locations.
- c. Interfaces with Globalstar: The system supports a maximum sustained data rate of 9.6 kbps, including a small framing overhead per subscriber channel. The UT position must be transmitted to the Globalstar gateways to support registration, at call initiation, and perhaps during the call.
- d. SMSS UT RF Subsystem: The UT receive RF subsystem must be designed with minimal losses, so that on average link closure requires nominal allocation of Globalstar transmitter power. Globalstar normally operates with no margin on the link but with 10 dB of dynamic power range. Fixed channel assignment, an onboard filter, or additional constraints on contact scheduling to avoid periods and locations of RAS activity may be required to meet flux density limits in RAS bands.
- e. Spartan SMSS User Terminal: A number of unique requirements are imposed by the SMSS UT, most notably the providing of position by an external source. The Globalstar fixed phone and car kit appear to use components which could potentially be used in a new configuration to support SMSS requirements. The reliability of these parts in a space environment, including susceptibility to single event upsets, must be

investigated. A set of guidelines must be developed for use in designing subsystems for short duration space missions.

f. Globalstar Ground System. Some modifications would be expected for:

1. UT supplied position
2. Frequent updates to the HLR/VLR system as the spacecraft position changes
3. Operation with regard to RAS flux density limitations.

Modifications such as these might be associated with a new user class, the SMSS user. If SMSS is not implemented at all Gateways, Gateway selection will be influenced by:

1. NASA specified availability and contact requirements
2. Gateway coverage, including the number of available beams and frequencies supported at each Gateway
3. Service area restrictions, including RAS limits
4. Globalstar Service Provider support, including a business case for the service provider to provide the service
5. Security issues.

In addition to Gateway impacts, the Globalstar control centers, the GOCC and SOCC would be expected to provide ephemerides and a tracking schedule to the NASA POC.

- g. Service Interface with Users: The NASA POC computes a contact schedule — a list of all possible contracts — for each user. The scheduling process may need to take Doppler and avoidance with RAS schedules into account as well as the Globalstar ephemerides and tracking schedule. Individual users may require additional assistance with troubleshooting, especially if multiple registrations and service providers are involved.
- h. User MOCC: Minimal impacts are imposed on the MOCC. It must receive the contact schedule, of all possible contacts, upload it to the spacecraft, and place calls at times based on that schedule. During the contact, the user MOCC interfaces to the PSTN via either modem or ISDN and receives telemetry and uploads commands as it would normally. It must also receive UT-initiated calls and page operators if required.

3.2 CONTACT/COVERAGE ANALYSIS

The primary goal of the contact and coverage study was to assess Globalstar's potential to meet the NASA requirement of one, five-minute contact per orbit. Secondary goals were to analyze the effect of a Doppler limit (applied to the L-band return link) and to determine

the effect of using a single Globalstar satellite (no soft handoff). A total of 56 simulations were performed with the following variations:

- a. Five user spacecraft altitudes (between 300 and 900 kilometers)
- b. Either four or eight Gateways were selected to provide optimal global coverage with little or no overlap between the sites
- c. Four user spacecraft inclinations (28, 35, 52, 90 degrees)
- d. Three Gateway minimum antenna elevation angles (10, 15, 20 degrees)

The overall conclusions from these simulations are:

- a. The SMSS can meet or exceed the NASA requirement of one contact per orbit through the use of eight Gateways for median cases (28 to 52 degrees) at lower altitudes
- b. On average, the service could achieve one contact per two orbits for polar orbiting spacecraft less than approximately 600 kilometers altitude
- c. Outage duration (the time between contacts) is highly dependent on the orbital inclination of the user spacecraft, while contact duration is dependent on both altitude and inclination
- d. Limiting the Doppler has little effect on the overall coverage provided
- e. Limiting support to one Globalstar satellite (no soft handoff) has little effect on contact frequency or duration for NASA spacecraft with altitude greater than 400 kilometers. Most contacts for spacecraft at higher altitudes are with a single Globalstar satellite. If a second contact occurs, it is typically much shorter than the first contact and often occurs during the same period as the first contact.

The suggested mission envelope, based only on geometrical visibility to Globalstar, is user satellites with inclinations between 28 and 52 degrees and altitudes up to 900 kilometers. For polar spacecraft, the NASA contact requirement cannot be met above an approximately altitude of 600 kilometers. Additional simulations for spacecraft between 600 and 900 kilometers altitude and between 52 and 90 degrees of inclination are required. Since most NASA polar users have orbits above 600 kilometers, it appears that the service may not be useful for the majority of NASA polar spacecraft. Further study is required to confirm this conclusion.

3.3 LINK ANALYSIS

An analysis of the links was performed based on the following assumptions:

- a. The user (Spartan) spacecraft is oriented randomly with respect to Globalstar, which implies using a worst-case spacecraft antenna gain of a required omnidirectional coverage
- b. Nominal intra- and inter-satellite interference, as carried in Globalstar budgets filed with the Federal Communications Commission (FCC)
- c. Forward link (Gateway to Spartan) and return (Spartan to Gateway) required Eb/No per FCC filing
- d. Eb/No includes improvement from the automatic retransmission protocol inherent in the Globalstar data transmission service
- e. The maximum link range for a Spartan at 300 kilometers altitude
- f. A single Globalstar is in view (no signal combining)
- g. Maximum transmission rate is 9.6 kbps
- h. A switch is used between two SMSS antennas, according to known Spartan orientation with respect to Globalstar satellites.

Multiple link budget options were analysed. The first two options used an Astrolab coaxial cable specified by Spartan and compared the minimum and average Spartan Effective Isotropically Radiated Power (EIRP). The next two options used lower loss Gore cable, comparing the average Spartan EIRP with a reduced field of view for Globalstar. Finally, link budgets for all above options were computed but with external Low Noise Amplifiers (LNAs) at the antenna.

The budget analysis showed that mitigating measures are required to close the link. While the Globalstar system will dynamically supply additional power to compensate for intermittent losses of up to 10 decibels (dBs) for obstructions, rain, etc., the system does not expect such losses to occur on a continuous basis. In normal operation, power is adjusted so that the link just closes; on average, the user will require 0 dB of margin. A service which imposed a continuous high demand on Globalstar satellite power would incur a higher calling charge, since it reduces Globalstar capacity and/or increases the noise level for other callers. The SMSS requires higher power than for a normal ground based user since:

- a. The SMSS budget operates at four times the transmission rate of the typical voice user (9.6 vs 2.4 kbps)
- b. Signals from multiple satellites are not combined as they are for the normal ground user

- c. The NASA LEO spacecraft attitude may not be pointing toward Globalstar. Globalstar link calculations assume that the ground user will orient the UT antenna toward the satellite constellation
- d. Additional cable losses are experienced in the spacecraft configuration.

Mitigation measures include requiring the spacecraft antenna system to be designed to minimize loss. Recommended measures include use of low loss cabling, and mounting the LNAs externally at the antenna rather than at the main body. Spartan transmitter power must be higher than the standard Globalstar phone over the full Globalstar field of view (108 degrees). With these measures, the forward and return links close.

In addition, link analysis showed that flux density limits in RAS bands would be substantially exceeded, as they are, to a lesser degree, for the nominal terrestrial hand-held terminal. Several provisions must be made to maintain flux density within required limits in these restricted bands. These provisions include use of a band reject filter and fixed assignment of channels at the high end of the Globalstar allocation (1625 MHz) to avoid use of frequencies near the restricted bands. Restricted operation may be required near RAS sites during observations. The Gateway selection and scheduling process may be used to avoid contacts near restricted sites during RAS observation periods. These measures could reduce significantly the number and duration of contacts, since not all frequencies and beams are available at all Gateway locations. Each Gateway is allocated the frequencies it needs based on the traffic requirements of the area served. Detailed contact analyses must thus take these issues into account to determine the feasibility of the SMSS service.

3.4 ONBOARD TRANSCEIVER

The strawman SMSS UT uses a standard hardware terminal, usable on all spacecraft, with spacecraft specific interface hardware. An initial block diagram, possible mechanical layout, size weight, and power estimates were developed for an SMSS UT. The block diagram draws upon components identified in the Globalstar fixed UT design as well as designs for UT being developed for the car kit. The Globalstar fixed UT was used since it is designed to report its fixed position to the Globalstar system. The interface block provides circuitry required to make the control and data signals of the specific user spacecraft host computer compatible with the UT central processor.

External LNAs are recommended to minimize link losses. An RF switch is included to eliminate the effects of power divider loss on received and transmitted signal power. A band reject filter is included in the package, which may be required as described in subsection 3.3.

A radiation impact analysis was performed, based only on the susceptibility of the Complementary Metal-Oxide Semiconductor (CMOS) Application Specific Integrated Circuits (ASIC) technology used in the standard Globalstar UTs. Shielding thickness was determined and included a 33% design margin. The estimated total dose hardness of the Globalstar CMOS ASICs is 4 kRad(Si). Estimated shielding requirements were developed for total, worst-case radiation dose per year, which occurs in orbits inclined between 60 and 90 degrees. To achieve a three-year life, no shielding is required at an orbit altitude of 300 kilometers. Between 12 and 24 mils of aluminum is required at 600 kilometers altitude and between 42 and 52 mils at 900 kilometers. A single event upset analysis has not been performed since parts information was not available.

The following assumptions were made to develop a Rough Order of Magnitude (ROM) cost and schedule estimate for development of a space-qualified UT:

- a. ASICs and memory can be used as-is, with no modifications to the chips
- b. ASICs and memory can be used in plastic or repackaged in hermetic packages without significant associated costs
- c. Any present parts or materials not usable for flight have available flight counterparts
- d. No significant electrical design or redesign will be required for the terminal assemblies
- e. Terminal specific test equipment will be available without significant cost
- f. All standard fixed terminal documentation and hardware will be readily available.

The main unit could be packaged in a unit measuring 8 by 6 by 3 inches weighing 7.1 pounds. It would draw 1.5 watts on standby and 20 watts on transmit. The size of the external LNA is based on the present Global Positioning System (GPS) LNA, and measures 4.5 by 0.5 by 2.6 inches with 0.25 watts of power. The size and weight of the main unit is driven by the band reject filter and the conservative estimates made for the size of the Globalstar terminal. The weight for both units includes extra aluminum for radiation and micrometeoroid shielding. The size could be significantly smaller if the band reject filter can be smaller or eliminated altogether.

Given the above assumptions, the ROM non-recurring cost for the main unit is \$1,543,000 which includes one Engineering Model (EM) unit and one unit for qualification testing. The recurring engineering ROM cost is \$133,000 and includes one protoflight unit and acceptance testing. The ROM estimate for non-recurring engineering for the LNA is \$466,000, which includes two EM units and qualification testing. The recurring engineering ROM cost is \$85,000, which includes one prototype, one flight unit, and acceptance testing. The estimated schedule is 20 months, assuming that system requirements are complete and

the effort starts with preparation of detailed UT specifications. To refine these estimates and validate the assumptions, hardware drawings and a parts list need to be made available.

SECTION 4 – RECOMMENDATIONS

Based on the study results, we conclude that follow-on efforts are both justified and required. We recommend that NASA develop the SMSS concept in three incremental phases as illustrated in Figure 4-1 and detailed in the subsections that follow. Phase One would validate SMSS feasibility from a technical, regulatory, and service provider standpoint and develop a demonstration plan. Phase Two would require detailed feasibility studies followed by development of requirements and high-level designs. Phase Three would detail design, development, and test of the SMSS service.

The proposed schedule is ROM and no estimates have been made for the required level of effort for any elements other than for the Phase Three UT effort. A caution is that there is no guarantee that the study team, including GLP and Qualcomm, will be able to devote the required resources to this effort within the specified time frames. In particular, GLP support must first be prioritized within its product evaluation program which has not yet occurred.

In addition, a study to develop guidelines for development of subsystems for short duration missions is also recommended.

4.1 PHASE ONE: VALIDATION OF SMSS FEASIBILITY

The SMSS concept developed in this study should first be validated and updated to result in a final operational concept, general service-level requirements, and a revised implementation plan. Risks should be identified and analyzed throughout to allow NASA and Globalstar to wisely decide whether or not to proceed with the SMSS project. This effort should include:

- a. Technical feasibility
- b. Regulatory feasibility (by GLP)
- c. Service provider feasibility
- d. Continued contact and coverage analysis
- e. Demonstration plan

Technical Feasibility

It is essential that GLP and its partner, Qualcomm, Inc., review, validate, and revise the concepts proposed in this brief study; assess their feasibility; and identify the major technical risks associated with implementing SMSS.

- a. First, GLP should validate and recommend revisions to the end-to-end SMSS concept developed in this study, including the impacts on the Globalstar system. GLP should provide its own opinion of feasibility and risks associated with implementing SMSS service. This effort includes reviewing the operations concept and the impacts on the Globalstar elements. In this effort, Qualcomm should document the interfaces required to provide SMSS.
- b. Second, GLP should similarly review the UT block diagram and supporting material, and provide recommendations on the SMSS UT design. When a list of UT components is available, Qualcomm or SS/L should evaluate the reliability of these parts in a space environment, including susceptibility to single event upsets.
- c. Third, the link budget analysis should be reviewed. This effort should include development of the specific link parameters of the SMSS offering (e.g., link budget, frequency assignments, scheduling mechanism, coordination with RAS observation time).
- d. Finally, the ROM schedule should be reviewed and revised and ROM costs developed.

Regulatory Feasibility

Globalstar should initiate contact with the FCC to determine if there are any regulatory issues associated with using these bands in low earth orbit.

Service Provider Feasibility

Service providers will decide whether to implement the SMSS service in their respective Gateways. They may also be able to use their assets to meet the NASA security requirements to inhibit the ability of hackers to flood a Gateway with calls directed to an SMSS-equipped spacecraft. The interest of service providers will be determined by a number of factors including serving national interests and the business case for the service. The study team recommends that contact with at least AirTouch – the U.S. Globalstar service provider – be initiated by NASA and/or Globalstar to determine their willingness to provide this service for NASA and to discuss NASA security requirements. Since global coverage is required, it may also be necessary to assess the interest of other service providers.

Continued Contact and Coverage Analysis

The analysis performed in the current effort was “ideal” in the sense that Gateways were selected solely to provide global coverage. A number of additional considerations will affect the choice of Gateways, as summarized in Section 3. Contact and coverage analysis must thus continue in parallel with other technical studies to determine whether the service continues to meet NASA requirements. An example of a more detailed study is to estimate the contact frequency and duration for a specific Spartan antenna with a specific gain

pattern, which requires treating the Spartan orientation as a random variable. Other examples are to determine:

- a. Impacts of Globalstar automatic gain control on contact frequency and duration
- b. Impacts of RAS effects
- c. Impacts of using identified Gateway sites as these are selected,
- d. Impacts of any limitations to frequencies available at these Gateways.

Modifications to the modeling software used for this initial study would be required to perform several of these more complex analyses.

Demonstration Plan

The proposed demonstration would use an early production UT "as is" onboard a shuttle flight to evaluate identified risks and increase technical confidence in the SMSS concept. Further study, including technical input from Qualcomm, is required to determine whether such a demonstration is deemed feasible using an unmodified UT and Globalstar Gateway. If a demonstration is feasible, a detailed demonstration plan should be developed, including a specification of the engineering tests that would be performed.

The overall project schedule would be revised and cost estimates prepared based on these studies. This phase ends with a project approval review approximately eight months after the effort is started.

4.2 PHASE TWO: SYSTEM ANALYSIS AND HIGH-LEVEL DESIGN

In Phase Two, the general SMSS service requirements are analyzed, leading to the development of system requirements and high-level designs to meet these requirements. The implementation plan is updated with revised costs and schedules, supporting a final assessment of overall feasibility. The effort should consist of:

- a. **System Analysis and Design:** An overall systems engineering effort is required since multiple elements are impacted. This should include risk analyses, including analyses of the certainty of contact in an emergency situation and the need for a backup system. The system design effort should result in an updated operations concept, an overall functional design, a set of system level requirements for the SMSS service, and revised schedules and cost estimates for the elements.
- b. **High-Level UT Design:** Studies are performed leading to development of high-level UT requirements as well as a UT functional block diagram.
- c. **Link Analyses and High-Level Antenna Design:** Studies are required to design an antenna which satisfies the link requirements while meeting the size, weight, and

power constraints of NASA satellites. A functional block diagram and high-level antenna requirements are developed.

- d. **Globalstar Ground System Requirements:** The additional functions required of the Globalstar system are identified, any necessary studies performed, and high-level requirements are developed as input to development of the system design.
- e. **Continued analyses** of the service's ability to meet the NASA contact and coverage requirements is performed. The items discussed above in subsection 4.1, must be continued throughout much or all of Phase Two.
- f. **A flight demonstration is designed, developed, and conducted.** Sufficient time must be allowed for acquisition of components and integration into the shuttle.

This phase ends with an final "go/no-go" decision, using the results of the above efforts to support a final assessment of technical and financial feasibility.

4.3 PHASE THREE: DETAILED DESIGN, DEVELOPMENT, INTEGRATION AND TEST

Finally, detailed subsystem specifications are developed, and these subsystems are designed, developed, and tested:

- a. **UT Design, Development, Test, and Flight Qualification:** A twenty month design, development, and flight qualification effort is executed
- b. **Antenna System Design, Development and Test:** The antenna system is designed, developed, and flight-qualified
- c. **Globalstar Ground System Software/Hardware Modifications:** Detailed requirements changes for the Globalstar system are developed; changes are developed and deployed
- d. **Gateway Selection:** Continued studies are performed, including contact and coverage analyses, to select the specific Gateways where the SMSS service would be deployed
- e. **NASA Point of Contact:** NASA must design and develop the functionality allocated to its POC
- f. **End-to-end system level operational tests** are required before the service becomes operational.

4.4 SHORT DURATION MISSION DEVELOPMENT GUIDELINES

NASA identified the need for a lower cost flight qualified UT to support low cost, short duration (three to six month) missions, and would tolerate a higher degree of risk in return for a lower cost. The lack of standards or guidelines for contractors to use in preparing a subsystem to meet a short-duration space mission makes it difficult to respond, since loss of the unit would lead to mission failure. It is recommended that NASA fund a small study to develop such guidelines for the three- to six-month mission. Such guidelines could be based on a reliability model of the spacecraft and/or subsystem, and would provide a mechanism for NASA and its contractors to agree on the magnitude and type of risks which are acceptable. The study team believes that such guidelines would make a substantial difference in cost and readiness of the Globalstar SMSS terminals.

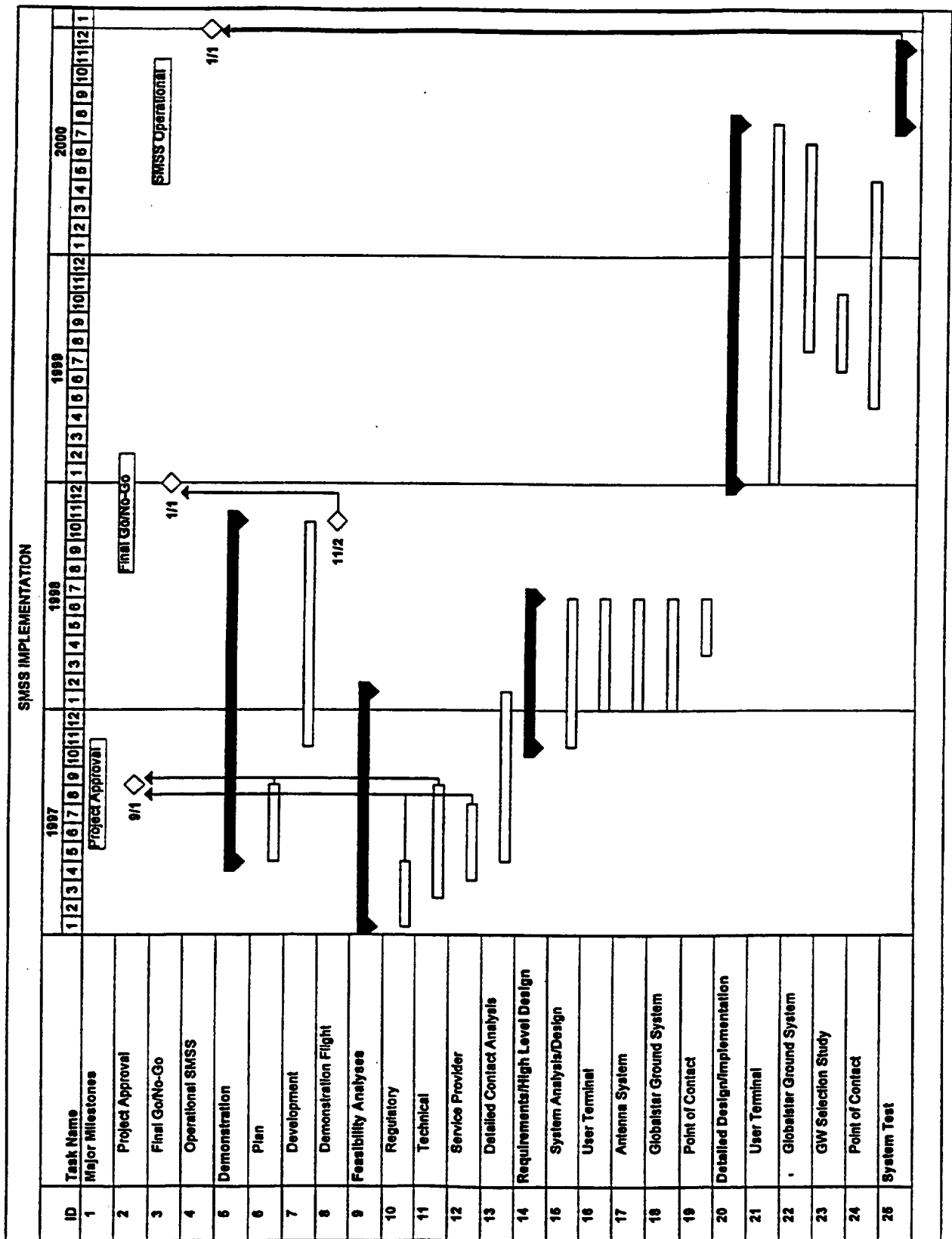


Figure 4-1. SMSS Concept

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